SPECIFICATION

Please replace the fifth and sixth paragraphs of page 7 with the following paragraphs.

Fig. 6 is a diagram illustrating portions of a spectrometer such as the one shown in Fig. 1 that has been adapted to employ light conductors;

Fig. 7 is another diagram illustrating portions of another spectrometer such as the one shown in Fig. 1 that has been adapted to employ light conductors;

Fig. 8 is a block diagram of an imaging spectrometer according to an invention originally presented in United States Patent Ser. Nos. 60/091,641 and 09/345,672, which are substantially reproduced below,

Fig. 9 is a flowchart illustrating the operation of the imaging spectrometer of Fig. 8;

Fig. 10 is a block diagram of the optical components of an alternative embodiment of an imaging spectrometer according to the invention originally presented in United States Patent Ser. Nos. 60/091,641 and 09/345,672;

Fig. 11 is a diagrammatic cross-section of an individual mirror element for the mirror array in the embodiment of Fig. 9; and

Fig 12 is a block diagram of the optical components of a third embodiment of an imaging spectrometer according to the invention.

Please replace the second full paragraph on page 12 with the following paragraph.

The sources can also be switched using sequences such as the Hadamard sequence, as described in provisional application no. 60/091,641, entitled Spectrometry Employing Mirror Arrays and filed July 2, 1998, and its child, application serial no. 09/345,672, filed June 30, 1999, both of which are herein incorporated by reference and substantially reproduced below. Such systems can receive an image using a single detector or a smaller array of detectors by illuminating different ones of a series of differently-directed sources according to a suitable sequence of spatial patterns. An

unswitched array can also be used in connection with a switchable mirror array, as described in the above-referenced application. A switching sequence can even be designed to derive both spectral and spatial information from the sample with a single detector.

Please insert the following material on page 13 after the first full paragraph.

The remainder of this application is a substantial copy of United States Patent Ser. Nos. 60/091,641 and 09/345,672, which relates to spectrometers and spectrometric methods that employ mirror arrays.

Background of the Invention

It is known to perform imaging spectrometry using a variety of methods, including methods that employ detector arrays, acousto-optic tunable filters (AOTF's), or liquid crystal tunable filters (LCTF's). A number of approaches have been investigated in order to extend these techniques to infrared imaging spectroscopy, such as the use of detectors that employ indium antimonide, mercury cadmium telluride, and platinum silicide, as well as micro-bolometer arrays. But these solutions have been quite expensive to implement, or have proved to be less than optimal for other reasons.

Summary of the Invention

In one general aspect, the invention features a two-dimensional imaging spectrometer that includes a source of light, an array of separately actuatable mirror elements optically responsive to the source, a spectral modulator being optically responsive to the source, a control processor portion having a control output provided to a control input of the array, a detector responsive to the array and the modulator, and a two-dimensional image processor portion responsive to the detector.

The control processor portion can be a Hadamard control processor operative to actuate the mirror elements in a series of Hadamard permutations, with the image processor portion including a Hadamard transform portion operative to combine signals resulting from reflections from the array while it is configured in the series of permutations. The source of spectrally

modulated light can include a Michelson interferometer. The two-dimensional image processor can further include a Fourier transform processor. The source of spectrally modulated light can be a source of modulated infrared light. The source of spectrally modulated light can include an interferometer responsive to a sample to be analyzed. The array can be made up of an integrated structure built with semiconductor manufacturing techniques. A sample can be placed between the array and the detector. The sample can define a reflection in an optical path between the separately actuatable mirror elements and the detector. The spectral modulator can be optically located between the source and the array of separately actuatable mirror elements. The spectral modulator can be optically located between the detector and the array of separately actuatable mirror elements.

In another general aspect, the invention features a two-dimensional imaging spectroscopy method that includes selectively reflecting an image according to successive mask patterns, spectrally modulating the image, detecting portions of the image reflected in the step of selectively reflecting and spectrally modulated in the step of spectrally modulating, and reconstructing at least one image from the light detected in the step of selectively reflecting.

The step of spectrally reflecting can operate according to a series of Hadamard permutations, with the step of reconstructing including a step of performing a Hadamard transform. The step of spectrally modulating can include constantly scanning light incident on an interferometer. The step of reconstructing can include performing a Fourier transform. The step of spectrally modulating can spectrally modulate infrared light. The method can further include the step of directing light reflected in the step of selectively reflecting toward a sample to be analyzed. The step of spectrally modulating can modulate light from a sample to be analyzed. The step of spectrally modulating can modulate the image before the step of selectively reflecting. The step of spectrally modulating can modulate the image portions after the step of selectively reflecting.

Systems according to the invention are advantageous in that they permit spectroscopic imaging using relatively inexpensive components. Such systems can be set up to obtain infrared images without requiring detector arrays. This is particularly advantageous for spectroscopic applications in the infrared and longer wavelength spectral regions, for which array detectors tend to be relatively expensive. In addition, systems according to the invention can employ a detector that is not well suited to array fabrication and thereby perform spectroscopic imaging in spectral regions that might not otherwise be viewable using existing array sensors.

Detailed Description of an Illustrative Embodiment

Referring to Fig. 1, an imaging spectrometer 10 includes an interferometer 14 having an optical input responsive to light radiated from a sample 12. The interferometer can be a Michelson interferometer. The interferometer is preferably operated at a constant scanning velocity in many cases, although this is not necessary in all cases. As is known, this type of interferometer acts as a spectral modulator that causes each wavelength incident upon it to acquire a temporal amplitude modulation proportional to its wavelength, permitting spectral information to be extracted from the signal using Fourier transform techniques. The light output from the interferometer is then collimated, such as by a lens 16, and projected onto a mirror array 18.

The mirror array 18 is an array of mirror elements 18aa...18nn. This array can be of any appropriate size, but is preferably a rectangular array having at least 64 rows and 64 columns. Each mirror element in the array can be separately actuated between selected and unselected positions by a control signal applied to a control input. The mirror array elements that are selected will reflect the light incident upon them toward a detector 22, while the remaining unselected mirror array elements will not. The detector can be a single-element infrared detector with an electrical output provided to an input of a processor 24.

The processor 24 can include modules that control the mirror array 18, that process incoming signals from the detector 22, and that generate display output to be presented to the user on a display 26. The processor 24 can include dedicated circuitry, a general purpose processor running special-purpose software, or a combination of the two.

The processor controls the actuation of the mirror elements in the mirror array according to a Hadamard series, although other series can also be employed. The Hadamard series is designed to permit a number of combined intensity measurements of sets of pixels to be taken and then to allow the image to be reassembled from these measurements while reducing noise through averaging via spatial multiplexing. Hadamard transforms are discussed in more detail in "Transform Techniques in Chemistry," edited by Peter R. Griffiths, Plenum Press, pages 175-182 (1978), which is herein incorporated by reference.

The processor is operative to combine the series of Hadamard-masked signals and derive a resulting image signal. The processor 24 also includes a Fourier transform module which performs a Fourier transform of the decoded signal and thereby extracts images at different frequencies based on the effects of the interferometer. These images can be enhanced by other signal processing techniques as well, and then displayed, stored, or otherwise treated.

In operation, referring to Figs. 1 and 2, the processor 24 begins by actuating the mirrors in the mirror array 18 according to a first mask permutation (step 102). The detector then acquires a sample of the signal for the current mask (step 104). This process is repeated for further Hadamard mask permutations and signals acquired for these masks until the Hadamard series is done (step 106).

Each acquisition can be performed for an image or a spectrum, and can be repeated for further images or spectra. Once all of the signals for the Hadamard series have been acquired, the processor 24 applies Hadamard and Fourier transforms to these signals (step 108). The processor can then further process the signal data and display, store, or otherwise treat corresponding images for one or more wavelengths (step 110). The processing and displaying can take place after all of the acquisitions, although it may be advantageous in some instances to begin some calculations in parallel with later acquisitions. If the spectrometer is not to acquire another data set, it can be shut down (step 112).

Referring to Fig. 3, an alternative embodiment of a spectrometer 30 according to the invention can analyze the transmission properties of a sample 38. Such a spectrometer can include an infrared source and an interferometer 32 which provides a beam that is colimated, such as by lens a 34, and reflected off of a mirror array 36 toward the sample. Part of the light incident upon the sample will be absorbed or reflected, and the remaining light will be focused, such as by a lens 40, onto a detector 42, which can be a single element detector. The output of this detector can be processed in a manner analogous to that presented in connection with Fig. 1 to obtain spectral image information about the sample.

While Michelson interferometers are preferred in the source, other types of sources may also be used, such as multiple sources or a single source with fixed filters or a filter wheel in the

optical path between the source and detector. For example, referring to Fig. 5, a third embodiment of a spectrometer 60 according to the invention can use multiple sources of different wavelengths and analyze a sample viewed in reflection. Such a spectrometer includes a first source 62, a second source 64, and a third source 66, which are each positioned to illuminate a mirror array 66, such as via a lens 64. Light from one or more of these sources then shines onto a sample 68. Some of this light is absorbed into the sample or transmitted through the sample, and the rest is reflected. The reflected light is focused, such as by a lens 70, onto a detector 72, which can be a single-element detector.

In this embodiment, spectral information is provided to the signal by selectively shining light from one or more of the sources at the array in successive acquisitions. The images can be derived by Hadamard techniques as described above. In one embodiment, the three sources 62, 64, 66 are light emitting diodes (LED's) that each emit at different wavelengths.

Referring to Figs. 3 and 4, the mirror array 36 can be created using semiconductor processing techniques. In one embodiment, each mirror element 36xx includes a silicon substrate 50 onto which a polymer strip 52 is mounted. The polymer strip has a mirror supporting portion onto which a mirror coating (e.g., aluminum) is deposited, and has a hinge portion 56 at its base. An electrical contact 58 electrically connects the conductive mirror portion to the substrate.

In operation, an addressing circuit responsive to the control input of the mirror array will select at least one mirror element 36xx and apply a high voltage to it. As a result, the substrate beneath the mirror element 50 and the mirror coating element will both be charged with charges of like polarity. This will cause the mirror element to separate from the substrate by electrostatic repulsion and thereby cease reflecting light in the direction of the detect sample 38 and detector.

In order to obtain a three or four dimensional data set, the instrument should record the intensity for a full series of mask settings and for a full series of retardation values corresponding to the spectral resolution of interest. There are several approaches which meet these criteria. The first is to record one interferometer scan for each mask setting. In this case it is preferable to use an interferometer which scans rapidly to reduce total data acquisition time. A second approach is to move the interferometer stepwise through all retardation values. At each retardation step, the entire sequence of mask settings can be executed. This is the preferable approach for most interferometers because the complete mask sequence can be iterated much faster than one interferometer scan. The third approach is a hybrid of these two; the mask settings are scanned sequentially while the interferometer retardation is scanned. The scanning may be synchronous or asynchronous.

The features of the various embodiments described above can be applied to different types of spectrometers, such as microscopic, macroscopic, endoscopic or remote-sensing spectrometers. The features can also be combined in different ways. Other mirror array structures can be employed, such as mirror array structures designed for video display technology. Such mirror arrays are available, for example, from Texas Instruments, of Dallas, Texas. Note that the instrument can be scanned to cover larger areas in a succession of area or line acquisitions. Using adjustable optics it may even be desirable to "focus in" on a feature observed at a lower resolution.